AN ECONOMIC COST MODEL FOR PATIENT-SPECIFIC INTERVERTEBRAL DISC IMPLANTS

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ABSTRACT

Back pain is a common concern amongst a growing population across the world today. Depending on the severity of a patient's condition, and after conservative treatment options have been exhausted, total disc replacement (TDR) surgery may be prescribed as a corrective treatment.

Several existing artificial disc implants are available on the market and are manufactured in standard sizes by means of conventional manufacturing processes – which typically involves machining operations. During surgery, surgeons try to select the most suitable implant size to match the patient's anatomy by pushing various trial sizes into the vertebral space before placing the final implant. This trial-and-error technique relies heavily on the level of experience of the surgeon and could lead to TDR device under sizing and inaccurate positioning of the implant, which could lead to implant subsidence and bone fracture.

As various imaging, software and manufacturing technologies have developed, the option for patient-specific implants by means of Rapid Manufacturing is becoming a realistic alternative. Patient-specific implants offer several potential clinical benefits to the patient, but it is important to investigate its cost implications. This paper discusses a cost model for patient-specific disc implants, and the potential advantages as well as challenges of using customized implants within the South African context.

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1 INTRODUCTION

Whether through direct or indirect means, intervertebral disc degeneration is a leading cause of back pain and disability in adults. Seventy to eighty percent of the population of the Western world experiences lower-back pain at one time or another [1], [2]. This could be caused by repeated injury to the back, or because of ageing [3]. It can induce pain as a worn disc becomes thin, narrowing the space between the vertebrae. Pieces of the damaged disc may also break off and cause irritation of the nerves. As the disc loses its ability to absorb stress and provide support, other parts of the spine become overloaded, thus leading to irritation, inflammation, fatigue, muscle spasms and back pain. This gradual deterioration of the discs between the vertebrae is referred to as degenerative disc disease (DDD), and typically involves a rupture of the annulus fibrosis and subsequent herniation of the nucleus pulposus.

Treatments for DDD vary according to a patient's condition and usually start with conservative, non-invasive to minimally invasive techniques. In other cases surgical procedures may however be prescribed where non-invasive methods have been ineffective. For severe cases, where the intervertebral disc has degenerated significantly, a total disc replacement (TDR) procedure may be prescribed in preference to a disc fusion procedure due to a growing concern that fusion may affect degeneration in the adjacent discs, [4], [5], [6], [7].

Most existing disc implants consist of endplates that are designed to be relatively flat in comparison to the concave boney endplate geometry. In order to accommodate the implant, the bone endplates are often surgically reduced to a flat plane and a slot is cut to receive the implant keel (fin-like protrusion that facilitates implant fixation). This action compromises the strength of the vertebra's cortical shell and reduces its ability to withstand pressure and can lead to implant subsidence or vertebral fracture [8], [9]. A more elegant solution will be to leave the endplates as intact as possible and rather adapt the shape of the implant to match the geometry of the vertebrae.

One approach may be to design the implant endplates with some measure of generic concavity to match that of the bone, based on morphometric studies of different population groups. However Van der Houwen contends that data on the prevalent shapes of the vertebral surfaces are scarce, citing 10 studies that have investigated the morphometry of vertebral bodies and their endplates, using a variety of methods (cadaver, CT, MRI, and X-Ray). He finally concludes that "the future may lie in custom-made implants, with for every person a perfect fit based on a pre implant measurement using CT data" [10].

Rapid Manufacturing (RM) has emerged over the past few years as a potential technology to successfully produce patient-specific implants for a variety of clinical applications [11]. Successful examples include cranioplasty implants [12], [13], oral and maxillofacial implants, finger joint implants [14], customized hip and knee implants [15], [16], [17], dental implants [18], and foot implants [19]. Despite these examples however, to the author's knowledge, very little work has been done to develop patient-specific intervertebral disc implants. With growing capabilities in both software and manufacturing technologies, these opportunities need to be investigated and developed wherever possible.

Along with the potential benefits, it is important to investigate the cost implications of patient-specific implants for TDR treatments. Technological progress in health care almost always results in an increase in cost to the patient, the hospital (if involved), the payer (insurer), or a combination thereof. Hospitals and payers are interested in keeping their

costs as low as possible while maintaining profit margins, and such medical insurers may refuse to cover procedures until more data becomes available from successful case studies and other clinical research results.

Economic modelling is used in a number of medical disciplines, although there has been little use of economic modelling relating to spinal procedures. Recent examples however include studies done by Polly et al. and Soegaard et al., investigating the cost effectiveness of techniques during lumbar spinal fusion [20], [21]. Another type of economic model is one comparing direct costs. Guyer et al. reported on a direct cost economic model comparing one-level TDR with three different one-level fusion procedures.

Soegaard proposed a framework using activity based costing with four different phases of perioperative care, namely diagnosis, admission, surgery and follow-up. Guyer's model assesses direct costs from both the hospital and the payer perspective (insurer or patient). This study combined Soegaard's framework with the South African National Health Reference Pricelist (NRP) to determine a cost model and discusses the potential advantages as well as challenges of using customized implants within the South African context.

2 RAPID MANUFACTURING PROCESS CHAIN FOR PATIENT-SPECIFIC DISC IMPLANTS

The process chain for customizing the design and manufacture of an intervertebral disc (IVD) implant was developed and is shown in Figure 1 below. Each step will be discussed shortly.

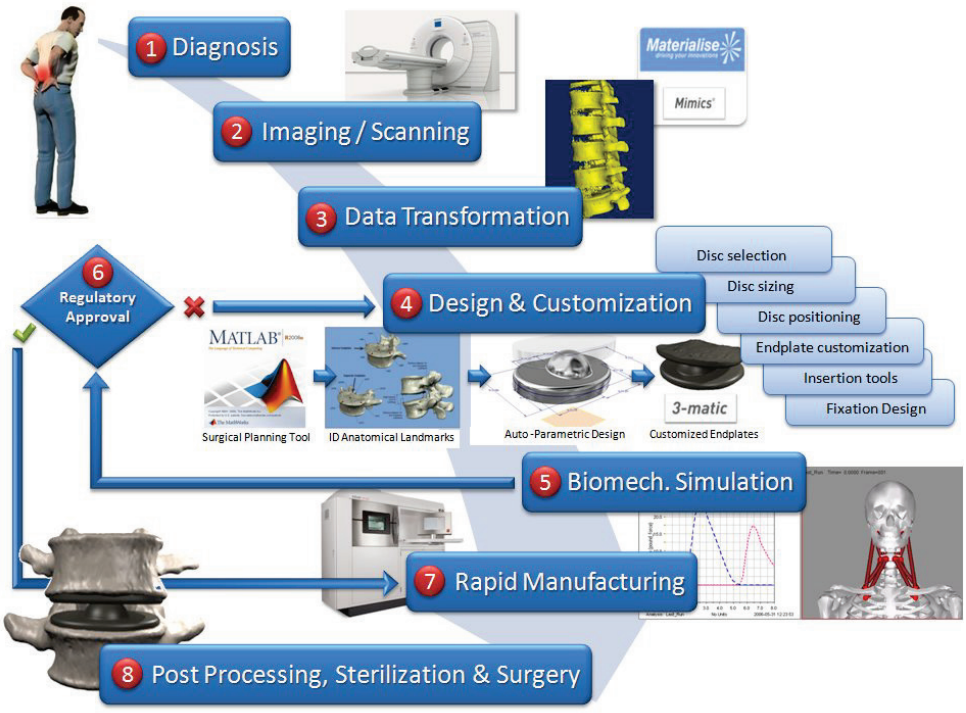

Figure 1: Clinical process chain for design & manufacture of patient-specific IVD endplates

2.1 Diagnosis

The first step in the process is to ascertain the patient's condition and eligibility for a TDR procedure. After diagnostic tests and three to six months of conservative treatment with no significant improvement, the patient is offered surgery based on a shared decision-making process. Based on a set of indications or contraindications, TDR may be prescribed as a surgical solution.

2.2 Imaging and scanning

Since information about the patient's bone geometry is required for the implant design, it is necessary to have a CT scan taken. CT scans should be acquired at a high spatial resolution with thin, contiguous image slices (0.75 – 1.25mm is ideal) and as small a field of view (FOV) as possible while still including the patient's external contour. No gantry tilt should be applied, and the patient must remain completely still through the entire scan.

2.3 Data transformation

The third step after acquiring CT scans is to convert the two-dimensional images into a 3D (STL file) model by means of a segmentation process. A variety of software solutions are available to perform this operation. In the case of our study, Mimics (Materialise, Belgium) was used.

2.4 Design and customization

The design and customization phase incorporates a user-friendly Surgical Planning Tool software which was developed in Matlab to allow surgeon involvement during the pre-surgical planning stage. Following the digital realignment of vertebrae, the surgeon identifies seven anatomical landmarks on the surface of each vertebral endplate. Six of these points are then used to define a spline curve which forms the footprint profile for the endplate of the intervertebral disc prosthesis. The seventh landmark on each vertebra defines the centre line on which the centre point of the spherical ball-and-socket joint connection is defined. Once the fourteen landmarks have been identified, their coordinates are exported to a semi-automated parametric 3D CAD model that has been designed using Autodesk Inventor Professional 2009 (Autodesk, California). The final step in the design process is to modify the implant endplates to match the geometry of the bone endplate surfaces. This is done by performing a simple Boolean subtraction between the implant and the vertebrae. STL files of the implant along with the bones were exported to 3-Matic software (Materialise, Belgium) where the subtraction was performed. The subtraction step was then followed by an undercut removal function, to ensure that the implant can be inserted without obstructions caused by undercuts.

2.5 Biomechanical simulation and regulatory approval

Several simulation models of the spine have already been reported in literature [22], [23], and as such, this study did not develop a new simulation model, but discusses its relevance and application in the process chain of implant customization as a whole, and within the context of regulatory approval processes. Figure 2 depicts an expansion of step 5 of Figure 1, showing the basic process flow during design improvements to the customized disc implant using simulation. A variety of patient information is collected as input variables to create a simulation model of the pathologic condition. A second generic simulation model can be scaled to match the patient's basic anatomy, age and weight. This generic "healthy" simulation model is then compared with the pathologic case. Based on an initial comparison, an assessment is then made in terms of what corrective action is needed to

rectify spinal alignment and vertebral positions. Recommendations and boundary conditions are then derived for the design and placement of an intervertebral disc implant. The implant is designed using the Surgical Planning Tool and 3D parametric CAD model described previously. Once designed, the pathologic simulation model is updated to include the implant. A new comparison between the implanted patient model and the generic "healthy" model is then made as before. This iterative process is repeated until a satisfactory resemblance between the models is achieved.

Regulatory approval of customized medical implants has the inherent difficulty that each product has, by definition, a unique design while still needing to adhere to stringent performance and safety standards. FDA and CE certification procedures require long and rigorous sets of tests which, at present, is not feasible for a customized implant design. Currently however, allowance is made for customized implants in general by having both the patient and surgical team sign consent before implantation proceeds. This situation is however not ideal as a long term solution. As simulation models increase in their ability to more closely resemble the natural dynamic behavior of the human body, it seems apparent that such techniques should become standard practice during the testing and approval of a spinal implant.

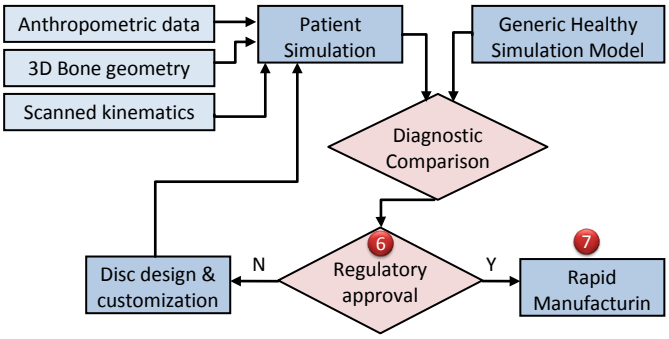

Figure 2: Simulation process flow in relation to regulatory approval

2.6 Manufacturing, post processing, & surgery

The ability of Rapid Manufacturing to produce end-use products directly in biocompatible materials such as titanium, makes it an ideal choice for manufacturing patient-specific spinal implants. As a demonstrator of the process chain described above, a generic, non-clinical ball-and-socket type implant was designed with an emphasis on endplate customisation. Figure 3 shows an example of the implant that was manufactured using Direct Metal Laser Sintering (DMLS) technology. The parts were produced on an EOSINT M270 machine, using Ti_6Al_4V powder material at the Centre for Rapid Prototyping and Manufacturing (CRPM) of the Central University of Technology (Bloemfontein, South Africa).

Titanium alloys are widely used as bio-implant materials, particularly for orthopaedic and osteosynthesis applications due to their low density, excellent biocompatibility, corrosion resistance and mechanical properties. They possess a stable passive oxide layer, which offers them an excellent corrosion resistance. Under conditions of wear and fretting, this oxide layer may release wear debris and metal ions which can cause adverse tissue reactions. In the case of Ti_6Al_4V, leaching of vanadium and aluminium is a major concern, which may cause peripheral neuropathy, osteomalacia and Alzheimer diseases [24], [25]. Thermal oxidation treatment of Ti_6Al_4V at elevated temperatures of between 500-800°C for between 8-24 hours can however improve its corrosion resistance further, reducing such risks [26]. The effect on corrosive resistance when using Layer Manufacturing

technology and the thermal oxidation treatment of such implants did not form part of this study, yet this important issue is noted for future related research studies.

Figure 3: Rapid Manufactured patient-specific Ti_6Al_4V intervertebral disc implant

3 TDR PROCESS CHAIN AND COST IDENTIFICATION

In order to develop a cost model of patient-specific disc implants for TDR, it is necessary to evaluate each step in the clinical process chain. These steps were investigated within the context of Soegaard's four different phases of perioperative care, namely diagnosis, admission, surgery and follow-up. Literature sources as well as extensive interviews with surgeons were used to derive the individual steps involved during these four stages. The South African National Health Reference Pricelist (NRP) was used, which is a baseline against which medical insurers can determine benefit levels and health service providers can individually determine fees charged to patients. This is a very structured document whereby medical procedures are listed and carefully documented by means of a coding system. The calculation of costs during each stage is a complicated process. Each diagnosis is assigned an ICD code (the International Statistical Class of Disease and Related Health Problems, 10^{th} Revision), while procedures are assigned a CPT (Current Procedural Terminology) code. All clinical procedures are linked to the NRP by means of a tariff coding system. In certain cases these tariffs may be modified when a patient's condition will affect such procedures. Finally, any pharmaceutical, surgical and healthcare consumables used in the procedure are assigned a NAPPI (National Pharmaceutical Product Interface) code. All costs refer to 2009 South African Rand values, and as such may appear to be conservative.

3.1 Diagnosis phase

During the diagnostic phase (outlined in Figure 4), a general practitioner will refer the patient to a specialist who performs a series of tests and prescribes a number of conservative treatment options. Following a diagnostic work-up, patients undergo an intensive rehabilitation course consisting of structured physiotherapy that incorporates cognitive training and a psychological assessment. Facet injections are performed as a diagnostic and therapeutic measure, being fully aware of its limitations. If there has been no improvement at the 3-month mark, patients are reassessed by the surgical team with input from physiotherapists. If there is no radiologic correlation and the patient continues to suffer from severe pain, pain medication is initiated. If it becomes apparent that the cause of the symptoms is surgically treatable, the patient is offered surgery based on a shared decision-making process.

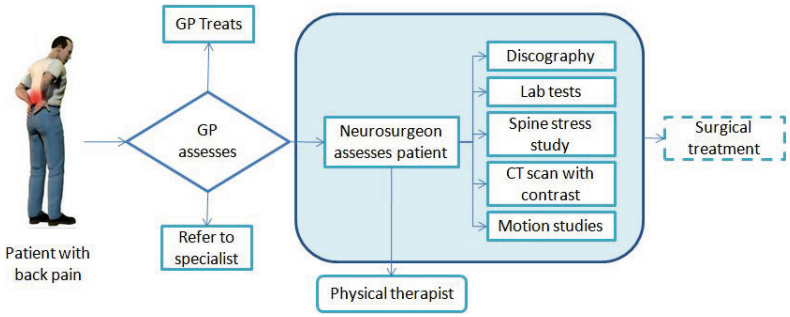

Figure 4: Process chain for the diagnostic phase

3.2 Admission phase

Once the patient is eligible for surgery, the admission phase is entered. Figure 5 shows an overview of the steps involved during this phase. Just prior to hospitalization, the design and manufacture of the patient-specific disc implant is initiated, as described earlier in Figure 1. Admission further involves the pre-operation assessment and examination of the patient by the neurosurgeon and anaesthetist. Other tests conducted prior to surgery also include measuring the patient's body mass index (BMI), bone density, and spine stress.

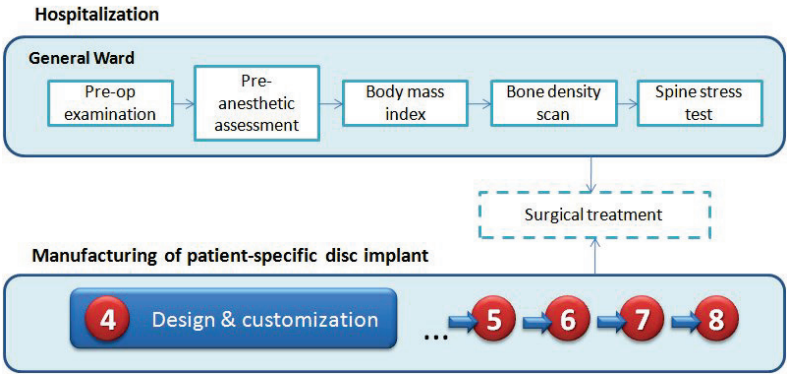

Figure 5: Process chain for the admission phase

The calculation of the manufacturing cost of the disc implant is based on machine setup, material cost, running cost, and post processing. Material cost is estimated from the part volume while running cost is factored against the total time to manufacture the part(s). Table 1 shows a comparative breakdown of manufacturing costs, indicating the inherent savings when producing multiple implants simultaneously.

Quantity	1	2	5	9
Machine setup	R 500	R 500	R 500	R 500
Material cost	R 231	R 462	R 1 154	R 2 078
Running cost	R 1 257	R 2 095	R 2 933	R 3 771
Post processing	R 900	R 900	R 900	R 900
TOTAL COST	R 2 888	R 3 957	R 5 488	R 7 249
Cost per implant	**R 2 888**	**R 1 979**	**R 1 098**	**R 805**

Table 1: Implant manufacturing cost breakdown

3.3 Surgery phase

The surgical phase of the TDR process is filled with variability that influences the overall cost of clinical treatment. Factors that cause this variability include:

- The location of the degenerated disc (cervical, thoracic or lumbar)
- The operating time
- The type of decompression surgery i.e. laminectomy, osteophyte removal, or discectomy
- The BMI of the patient
- The age of the patient
- Whether the patient is a smoker or not

Figure 6 shows that during the surgery, certain vital signs are monitored and anaesthesia is administered. The operation commences as an access surgeon opens the wound. The surgeon performs the necessary discectomy, followed by preparing the vertebral endplates. After the artificial disc is placed, the access surgeon once again closes up the wound.

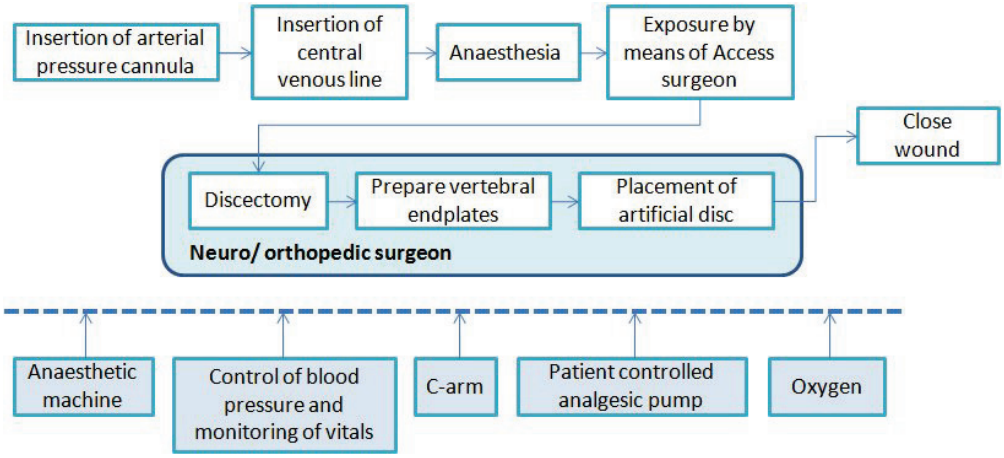

Figure 6: Process chain for the surgical phase

3.4 Follow-up phase

Figure 7 shows the steps involved during the follow-up phase. After the operation, the patient is taken to the high care ward for observation. Once stable, the patient is moved to the general ward for recovery. The patient is discharged after two days and returns for a follow-up visit after one week. Further follow-up visits and subsequent tests assist the patient during long term recovery.

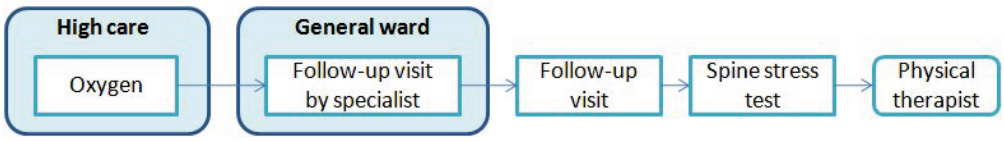

Figure 7: Process chain for the postoperative follow-up phase

3.5 Process costing

With reference to the National Health Reference Pricelist (NRP), Table 2 shows the costs that were calculated for each of the different phases described above. Figure 8 provides a

cumulative overview of the escalation in cost as the phases progress. Diagnosis comprises 10% of the cost, admission 20%, surgery comprises the largest portion at 68% and follow-up only 2%.

Diagnosis	General Medical Practice	R 211.30
	Consultation Neurologist	R 326.60
	Contrast medium	R 203.10
	Discography	R 381.30
	Anesthesiologist	R 195.30
	Stereotactic equipment used	R 1 480.10
	Spine Stress Studies	R 121.20
	CT lumbar spine: pre and post contrast	R 244.20
Admission	Pre-anesthetic assessment	R 201.00
	First Hospital Consultation	R 326.60
	Anesthesiology	R 201.00
	Spine Stress Studies	R 121.20
	Bone Densitometry	R 848.60
	High Care accommodation/day	R 1 465.35
	General Ward accommodation/day	R 2 918.75
Surgery	Surgery room	R 6 466.50
	C-Arm	R 802.25
	Patient Controlled Analgesia Pump	R 357.30
	Prosthesis	R 2 880.00
	Access Surgeon	R 1 244.80
	Setting of sterile tray	R 77.80
	Insertion of arterial pressure cannula	R 194.50
	Insertion of central venous line	R 194.50
	Oxygen during surgery	R 74.25
	Anterior Spinal Osteotomy with disc removal	R 2 450.70
	Anesthesiology	R 6 153.00
	Contrast medium	R 203.10
Follow-up	Oxygen, recovery room or emergency room	R 16.40
	Spine Stress Studies	R 121.20
	Contrast medium	R 203.10
	CT spine: pre and post contrast	R 244.20
	Physical Therapist: Mobilization of joints	R 88.50
	TOTAL	**R31 025.70**

Table 2: Cost estimations for TDR process chain with patient-specific implant

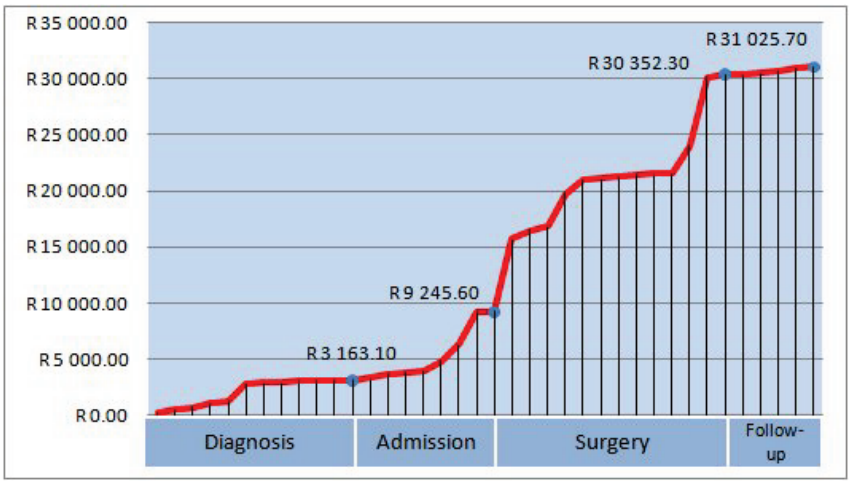

Figure 8: Cumulative costs for lumbar TDR surgery

4 CONCLUSION

The results of this study show that there are indeed significant potential benefits that can be achieved through the use of customization during the design and manufacture of intervertebral disc implants. With the design and manufacturing process that has been proposed, these and other potential benefits can and should be developed for the improvement of existing disc implant designs. Further research is required to develop the necessary insertion tools and fixation designs, of which there are many alternatives that Rapid Manufacturing can offer with its ability to create complex geometry.

An overview of a cost model for TDR within a South African context was also presented. A cumulative breakdown of costs for TDR indicated that 68% of costs are incurred during the surgery and implant manufacturing phase. Up to 72% reduction in manufacturing costs can be achieved when producing multiple implants simultaneously. Furthermore, the potential time that can be saved during surgery by using a patient-specific implant is still a significant topic for further study.

Although there are several significant challenges ahead (both technical and regulatory) the prospect for customisation in the spine is indeed an exciting one with far reaching potential benefits to the patient specifically and to health care in general.

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